

On The Fringe Field Of Wide Angle LC Optical Phased Array

Xinghua Wang (1), Bin Wang (1), Philip J. Bos (1), James E. Anderson (2), John Pouch (3), Felix Miranda (3), and Paul F. McManamon (4)

(1) Liquid Crystal Institute, Kent State University, Kent, OH

(2) Hana Microdisplay Technologies, Inc., Twinsburg, OH

(3) NASA GRC, Cleveland, OH

(4) Wright-Patterson AFB, OH

Abstract Text:

For free space laser communication, light weighted large deployable optics is a critical component for the transmitter. However such an optical element will introduce large aberrations due to the fact that the surface figure of the large optics is susceptible to deformation in the space environment. We propose to use a high resolution liquid crystal spatial light modulator to correct for wavefront aberrations introduced by the primary optical element, and to achieve very fine beam steering and shaping at the same time. A 2-D optical phased array (OPA) antenna based on a Liquid Crystal on Silicon (LCOS) spatial light modulator is described. This device offers a combination of low cost, high resolution, high accuracy, high diffraction efficiency at video speed. To quantitatively understand the influence factor of the different design parameters, a computer simulation of the device is given by the 2-D director simulation and the Finite Difference Time domain (FDTD) simulation. For the 1-D OPA, we define the maximum steering angle to have a grating period of 8 pixel/reset scheme; as for larger steering angles than this criterion, the diffraction efficiency drops dramatically. In this case, the diffraction efficiency of 86% and the Strehl ratio of 0.9 are obtained in the simulation. The performance of the device in achieving high resolution wavefront correction and beam steering is also characterized experimentally. Excellent agreement is shown between theory, simulation and experimental results, which validates the accuracy of the simulation. The non-uniformity of the LCOS across a clear aperture is less than $1/10 \lambda$ for all grayscale. The beam steering accuracy is higher than $10 \mu\text{rad}$, or $1/10$ of the diffraction limited beam divergence, at high efficiency. One main design issue for the liquid crystal device is how to achieve wide angle steering. This requires the pixel size to be close to the operational wavelength. The fringe field-caused interpixel coupling effect plays a very important role in this case. When the pixel size is smaller than $4 \mu\text{m}$ in an 8 pixel/reset scheme, the diffraction efficiency is very low. Optimization of the phase profile can be achieved by putting a higher voltage on the high voltage pixel and a lower voltage on the low voltage pixel. An optimized design with a $1 \mu\text{m}$ pixel size and a $0.5 \mu\text{m}$ gap between electrodes has been achieved for device operation at 632.8 nm , but not for 1550 nm . The reason is for the 1550 nm operation, the cell gap needs to be very thick which worsens the interpixel coupling from the fringe field and the device ends up not having enough retardation. Correcting for the aberration in light weight deployable large optics has been studied using the wave optics simulation, or CODE V software, and through experiments. In the wave optics simulation, 10 waves (P-V at 632.8 nm) of surface deformation of defocus on the primary mirror of a Ritchey-Chretien telescope with a 1 meter clear aperture is corrected to the diffraction limit, with a Strehl ratio of 0.63 in the simulation. Experimentally, an 8 inch diameter $f/D=5$ parabolic mirror is set up to simulate the Ritchey-Chretien telescope. A Mach-Zehnder interferometer is used to measure the wavefront aberration induced by a thick glass placed in front of the 8 inch mirror. 34.8 waves P-V of high order aberration at the exit aperture of the system is corrected to the diffraction limit. The residual wavefront error is less than $1/30 \lambda$ R.M.S. Based on the results from the performance of the LCOS and wave optics simulation, the prediction for the diffraction efficiency of the above system using an LCOS device to achieve compensation for large aberrations in a high magnification system has been given.

On the fringe field of wide angle LC Optical Phased Array



*Mark (Xinghua) Wang, Bin Wang, Philip J. Bos
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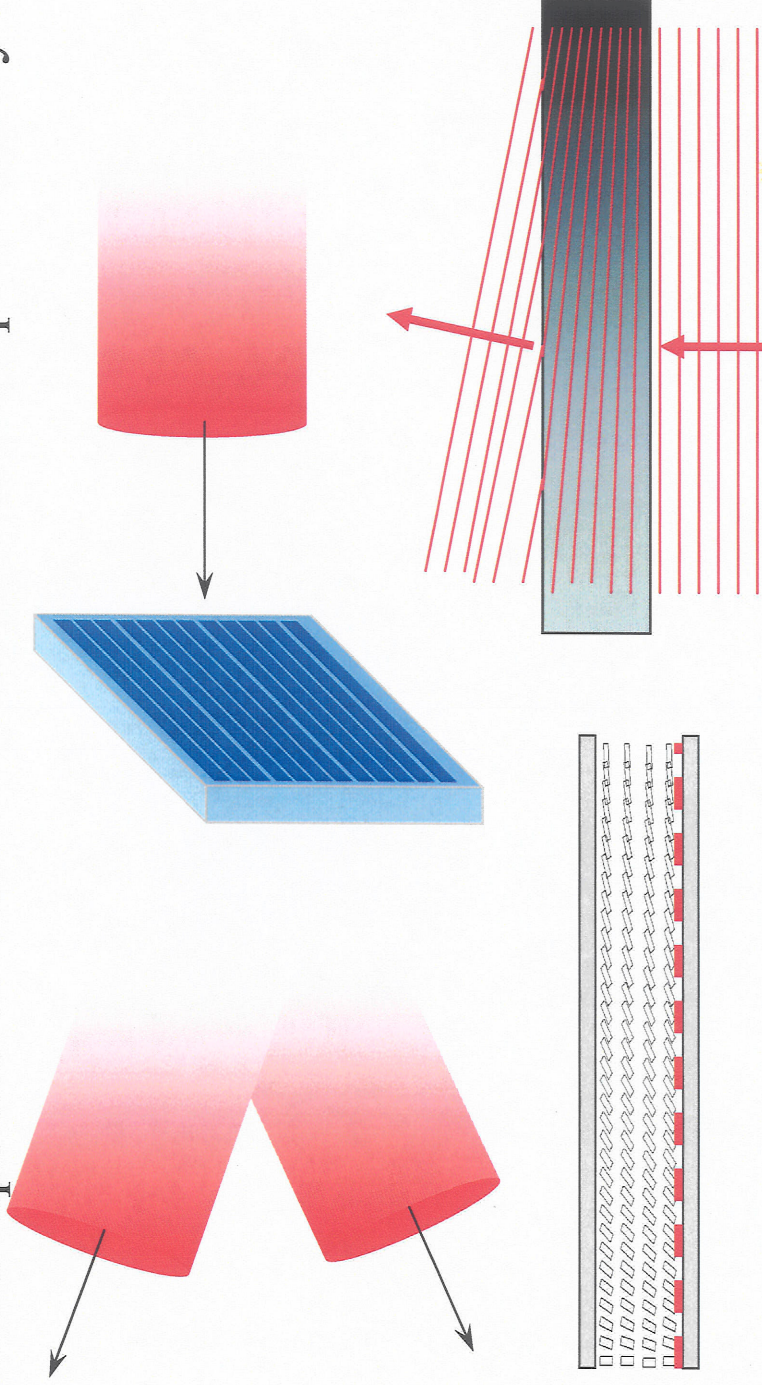
Outline

- Basic concept
- 2-D LCoS OPA for beam steering and high resolution wavefront control
- Toward wide angle LC OPA
- Influence factor of Diffraction Efficiency of wide angle LC OPA
- Optimizing LC OPA

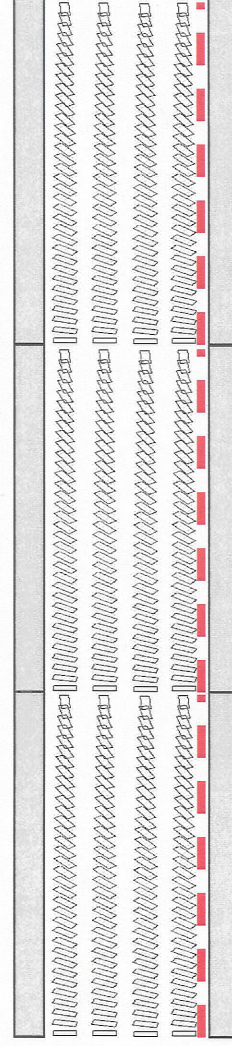
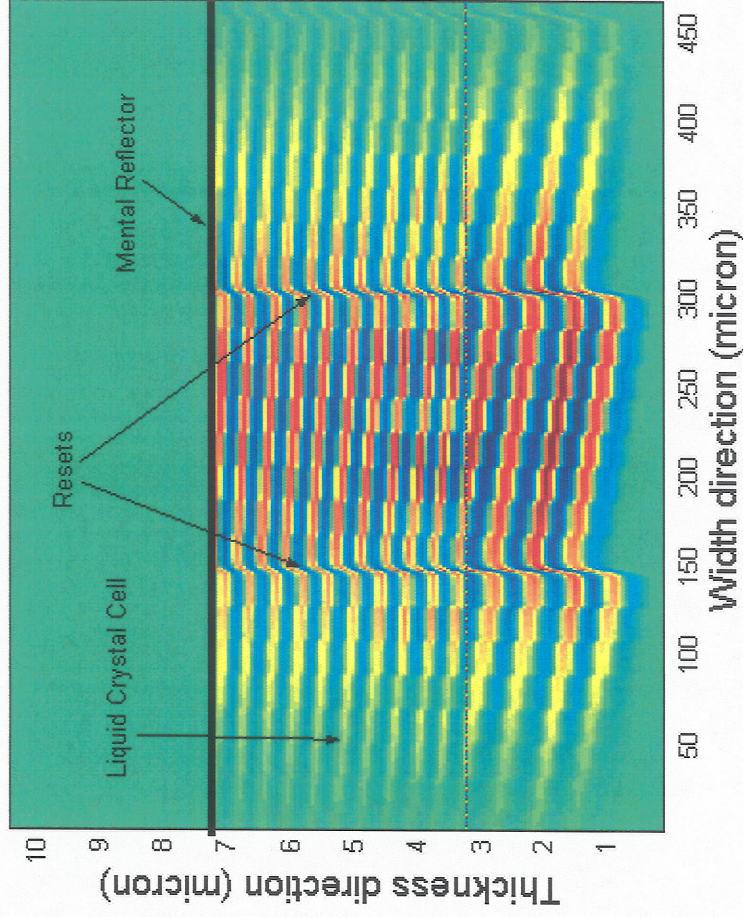
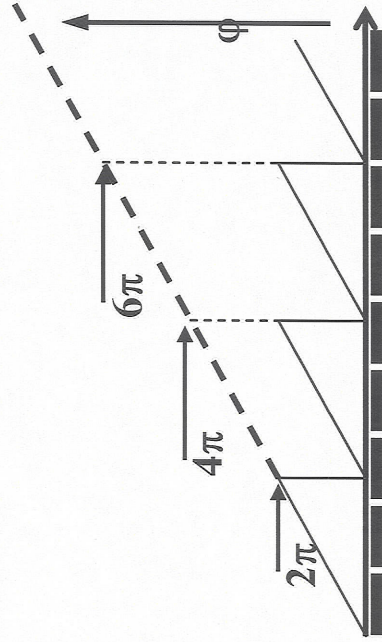
What is Optical Phased Array

1-D Optical Phased Array:

line shape active element that can induce phase delay



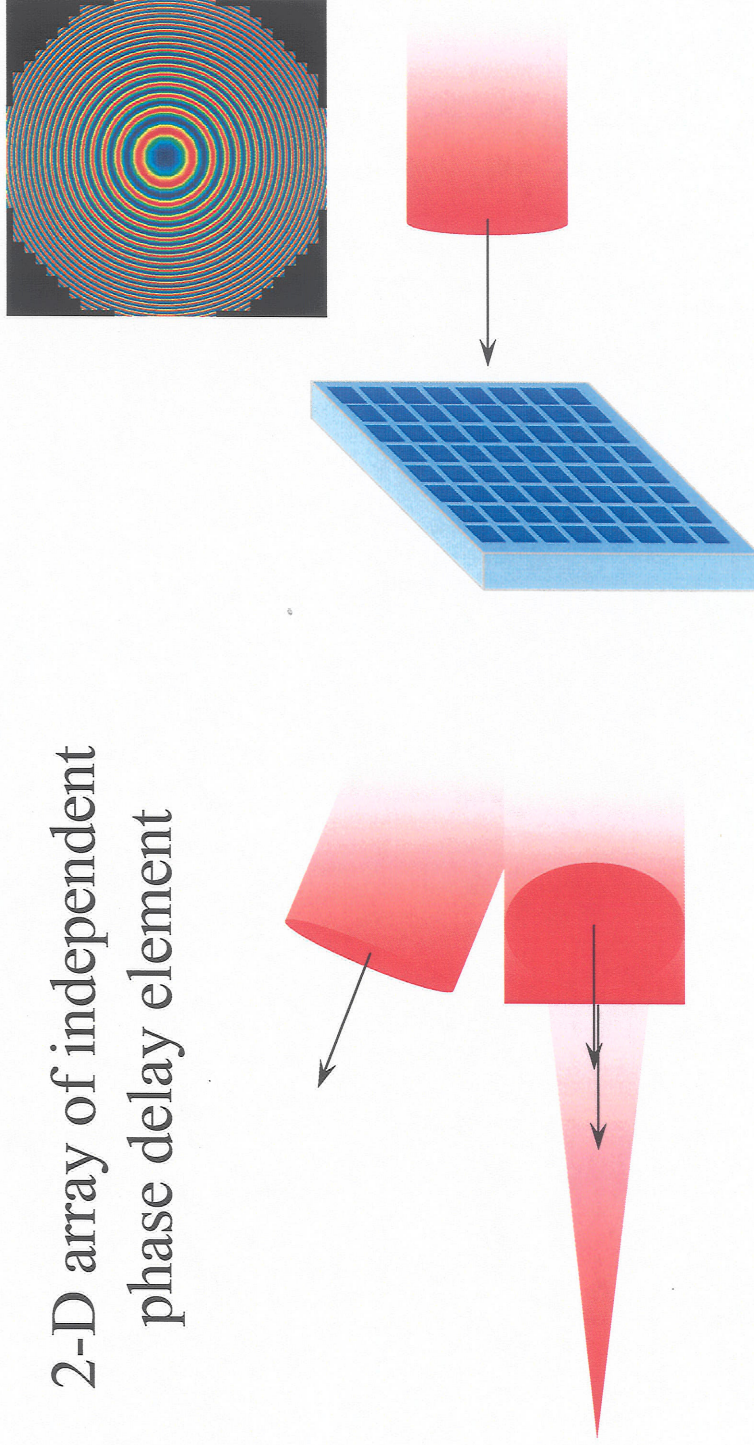
Light Propagation in LCoS



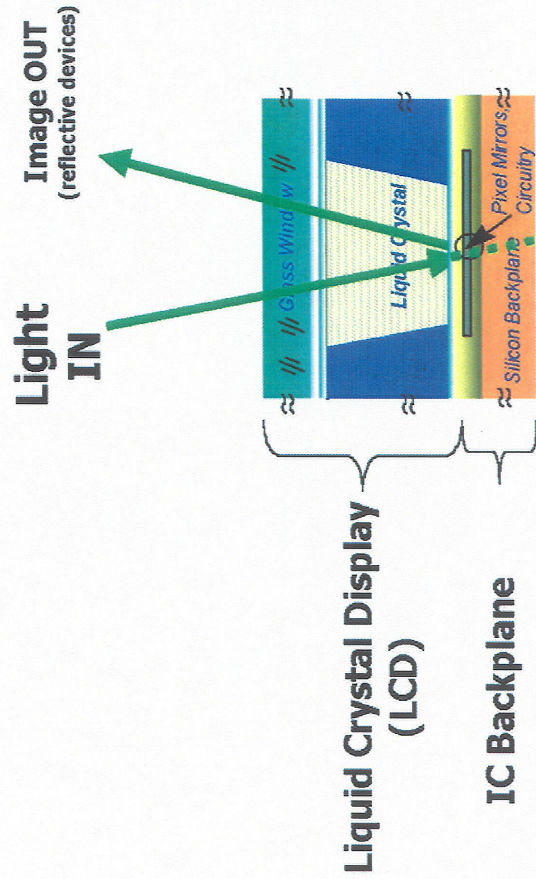
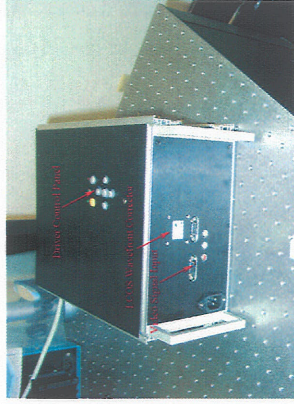
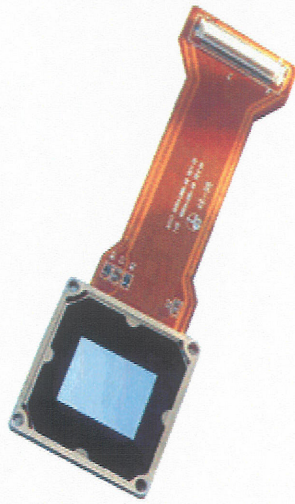
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2-D Optical Phased Array

2-D array of independent
phase delay element



Liquid Crystal on Silicon Spatial light modulator



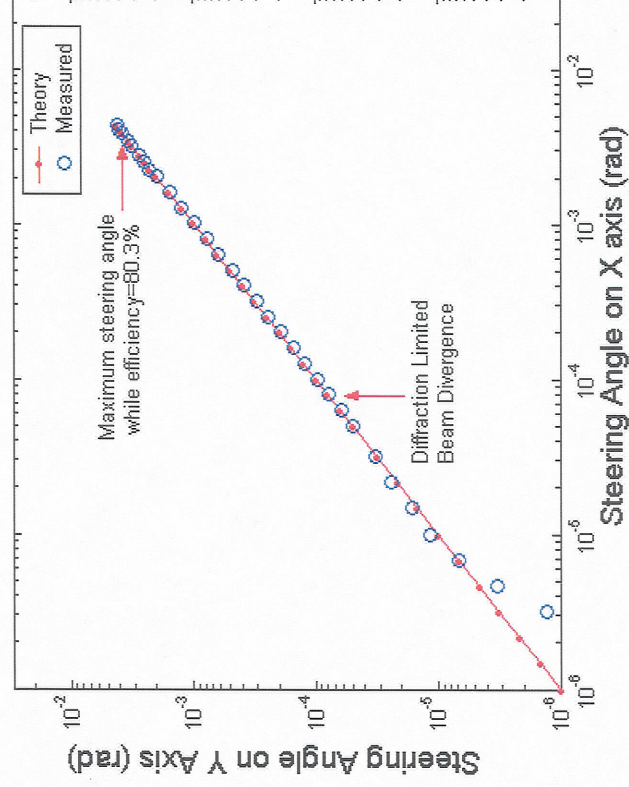
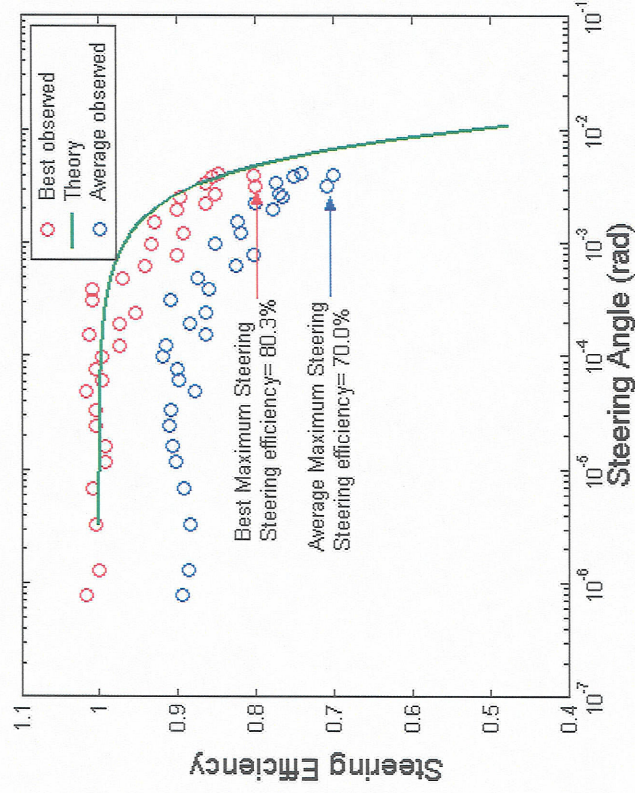
Resolution:	1024*768
Pixel Spacing:	19.4 m
Aperture:	20mm*15mm
Reflectivity:	80%
Filling factor:	96%
Speed:	50Hz, 25Hz, 5Hz
Effective stroke length:	0.7 m, 1.3 m, 2.5 m

2D LCOS OPA steering efficiency/accuracy

Steering Range: ± 4 mrad (0.23°) on X and Y axis

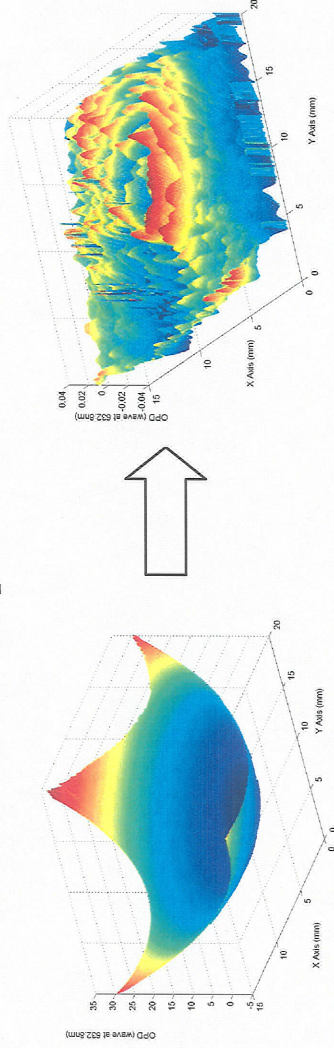
Steering Accuracy: $10\ \mu\text{rad}$ (1/10 diffraction limited beam divergence)

Steering Efficiency: $>80\%$



High resolution wavefront control in large optics

Wavefront aberration
introduced by the primary
mirror of 8 inch telescope



Before correction:

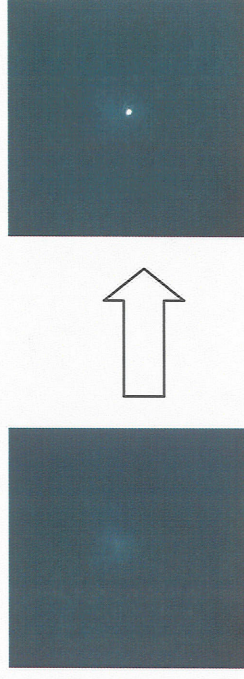
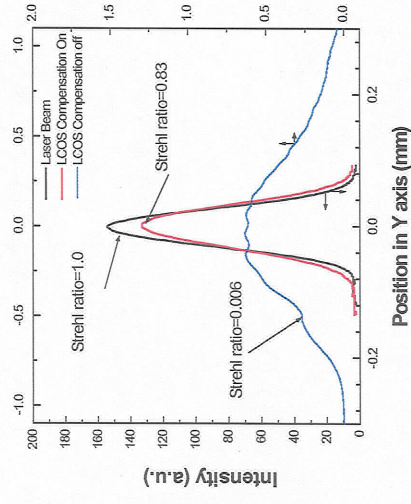
34 waves of aberration P-V

Strehl ratio 0.006

After correction:

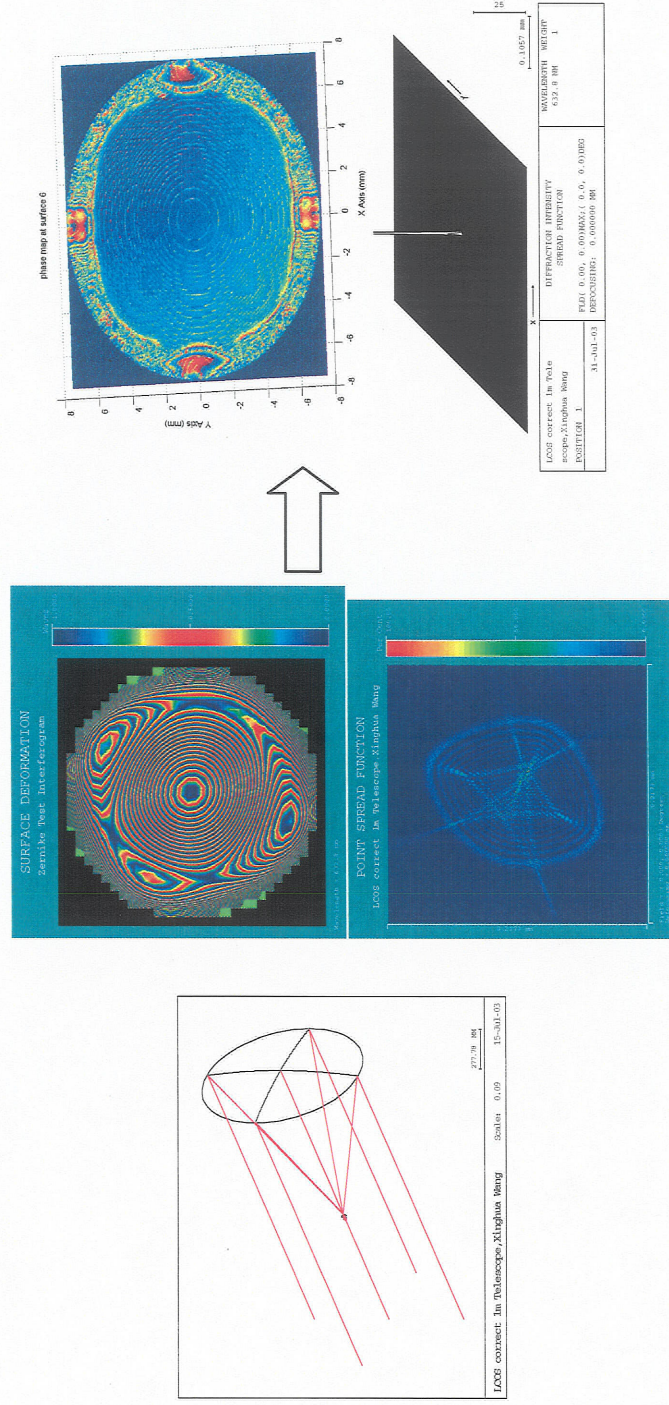
1/10 wave of aberration P-V

Strehl ratio=0.83



Diffraction limited performance!

Maximum aberration can be corrected

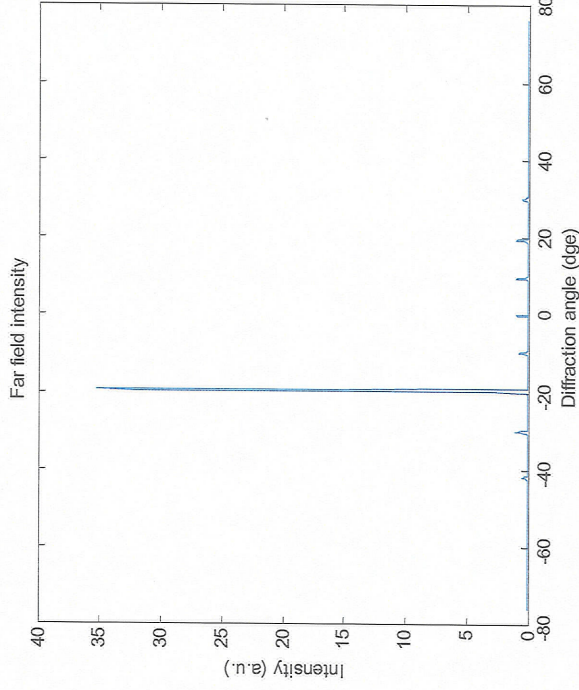
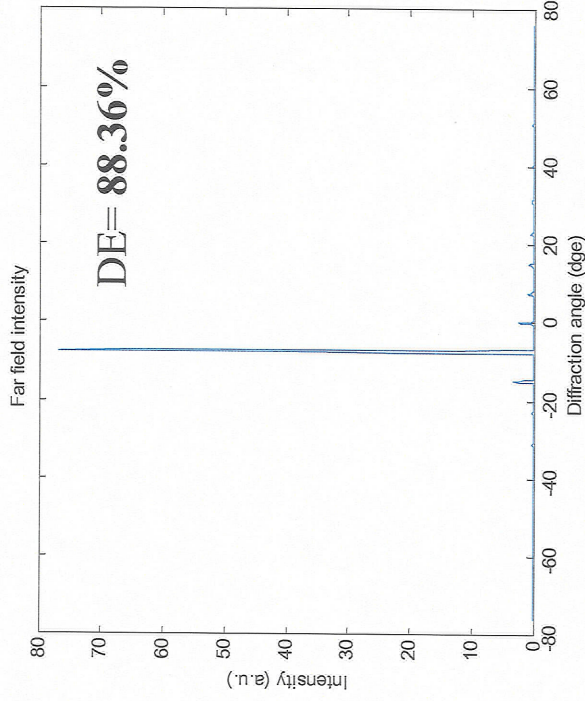


$$\eta_{total} = 90\% \times 90\% \times 0.63 = 0.51$$

Correct 48 waves P-V, or 20 waves R.M.S. of primary defocus with a 750 x 750 pixel LCoS 2-D OPA

Toward wide angle LC OPA:

-Theoretical limit of wide angle LC OPA



Diffraction efficiency of wide angle OPA with ideal LC director configuration.

- (a) 7.4° LC OPA for 1550nm, grating period=12um, $\Delta n=0.35$, Cell thickness $d=2.21\mu\text{m}$, reset order=1, FDTD grid=40 grid/wave, DE= 88.36%, (a) 19.4° LC OPA for 1550nm, grating period=3 um, $\Delta n=0.5$, Cell thickness $d=1.0\text{ um}$, reset order=2, FDTD grid=50 grid/wave, DE= 62.89% ?*

It is possible to achieve wide angle steering

Optimize LC OPA

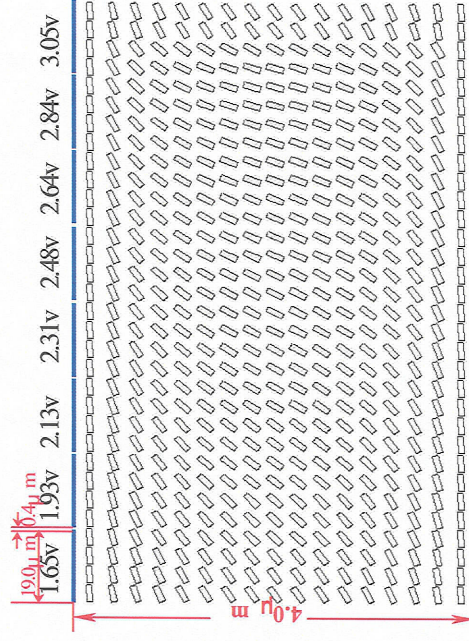
- The effect of fringing fields in a real device
- Optimization of OPAs

Influence factor of diffraction efficiency of LC OPA

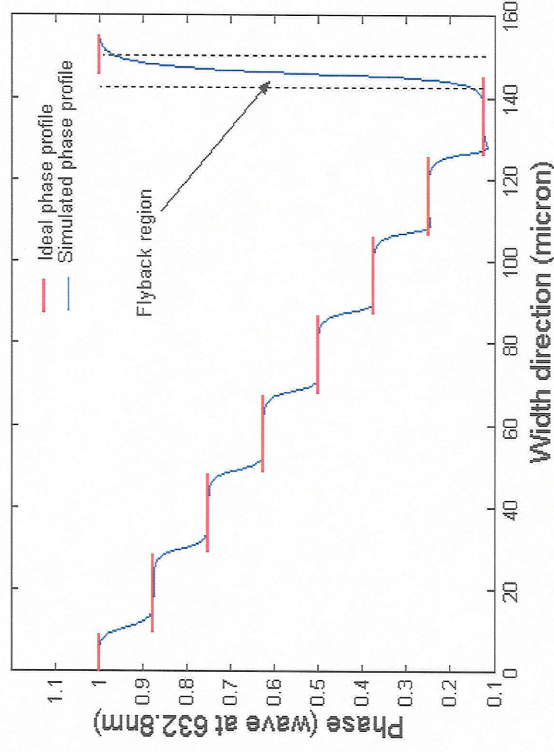
- Cell Thickness
- Voltage profile
- Grating period
- Inter-pixel gap (Electrode geometry)
- Optical axis (rubbing parallel/perpendicular to electrode in 1-D OPA case)
- $\Delta n \cdot d / \lambda$ value
- Pretilt angle
- Elastic constant of LC material

2D LC director modeling

$$F = \int \frac{1}{2} \{ K_{11} (\nabla \cdot n)^2 + K_{22} [n \cdot (\nabla \times n) - q_0]^2 + K_{33} [n \times (\nabla \times n)]^2 - \bar{D} \cdot \bar{E} \} dV$$



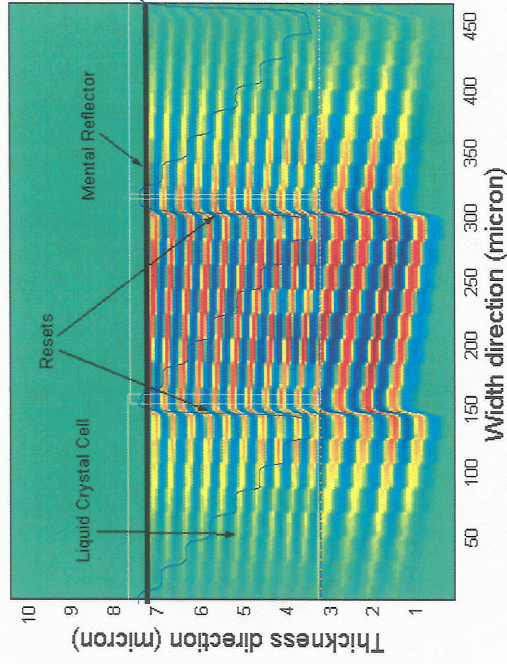
Director configuration of an 8 electrode LC OPA



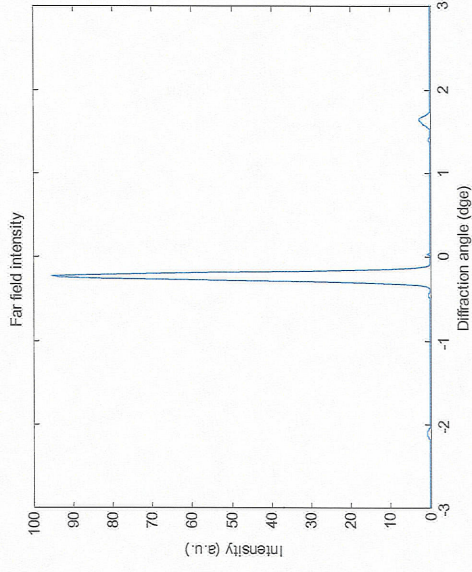
Phase profile of the 8 electrode LC OPA: Simulated phased profile versus the ideal stair like blazed profile

Finite Difference Time Domain Optical simulation

Light propagation in 24 electrodes with 3 resets



Simulated far field efficiency and beam profile



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Increase the spatial resolution of LCOS leads to inaccurate phase profile

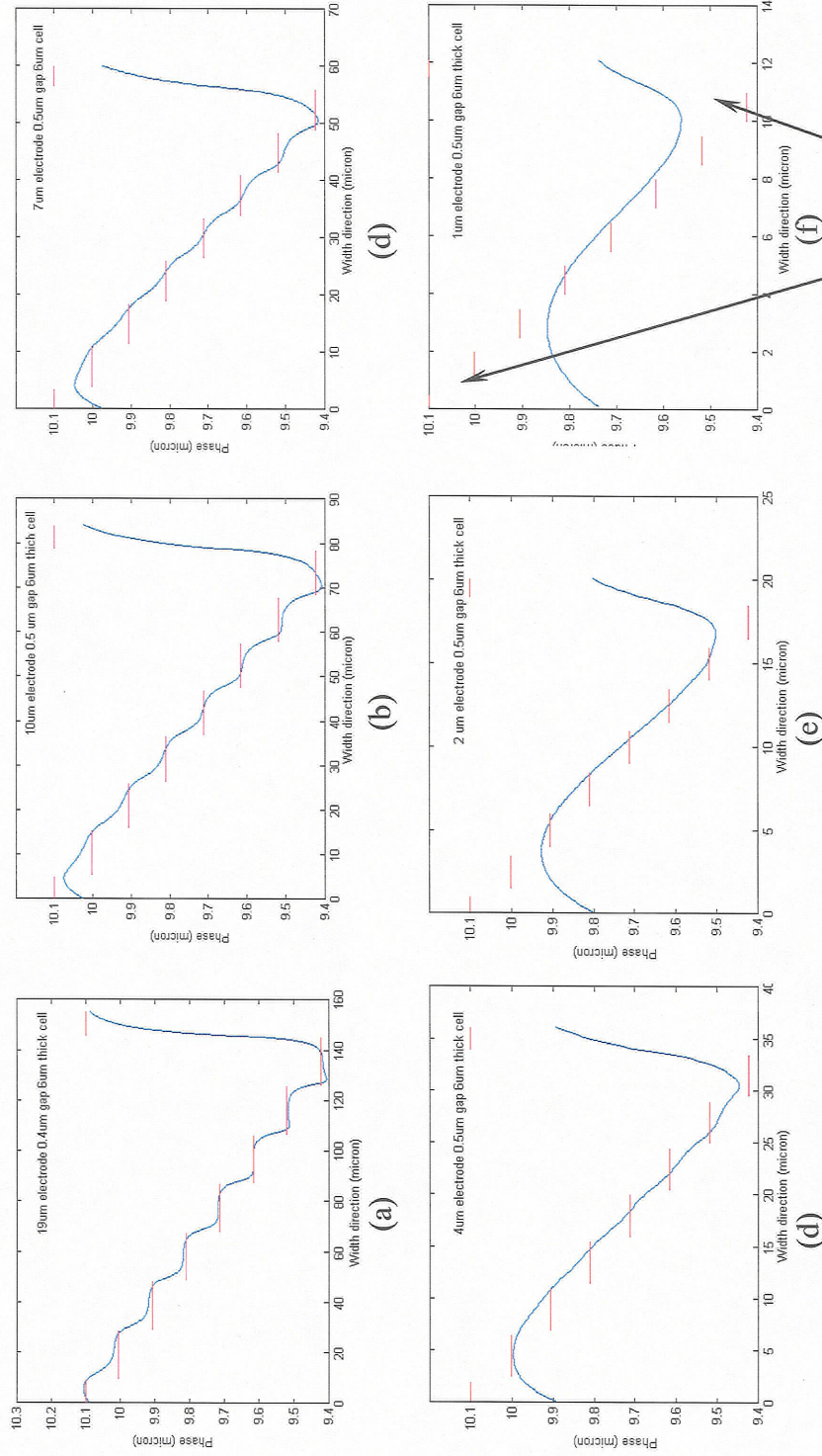


Figure: Simulated phase profile of liquid crystal device with different electrode configuration.

MLC 6080 $\Delta n=0.20$, $d=6 \mu m$.

Pixel spacing= (a) $19.4 \mu m$

(d) $4.5 \mu m$

(b) $10.5 \mu m$

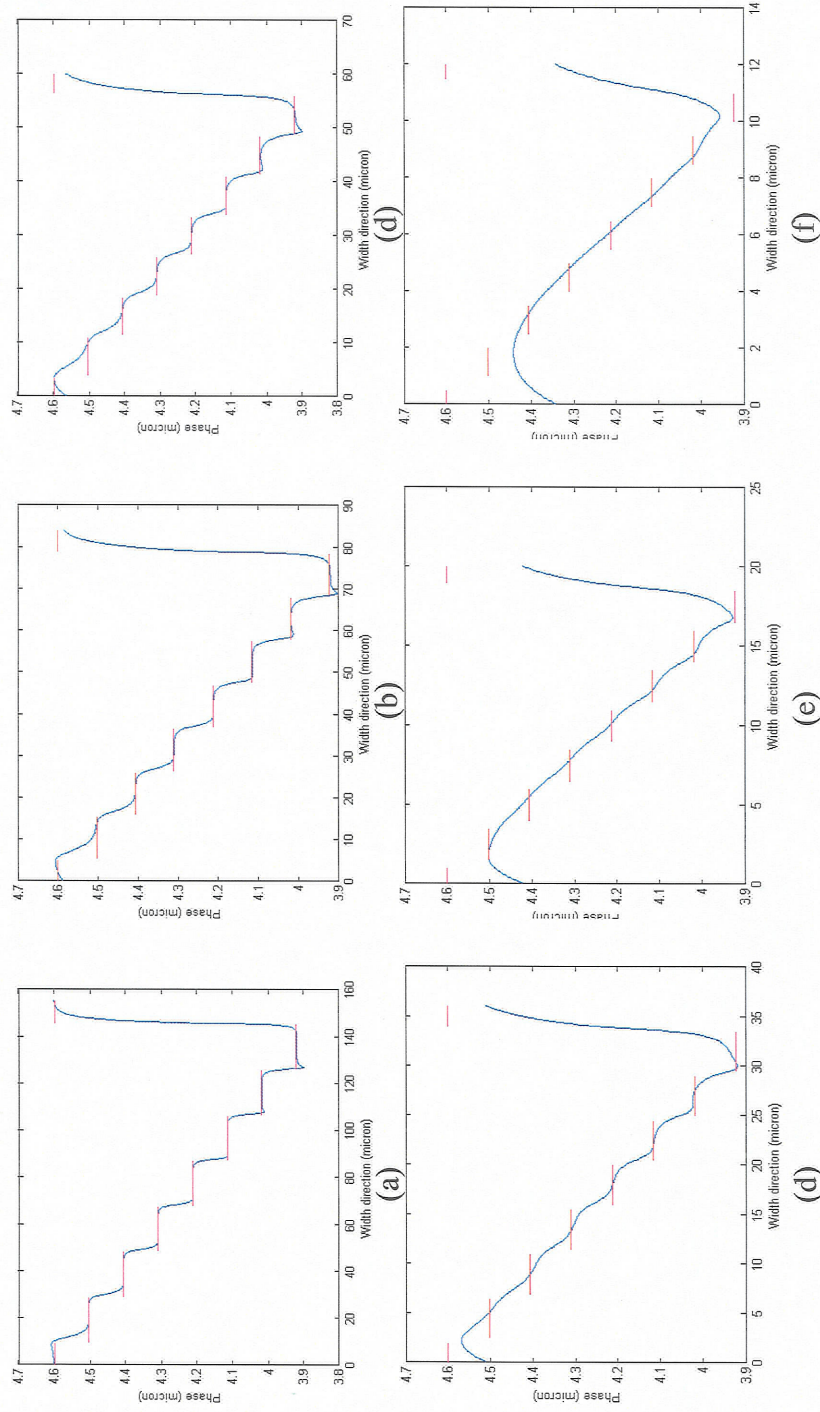
(e) $2.5 \mu m$

(c) $7.5 \mu m$

(f) $1.5 \mu m$

Increase cell thickness will worsen this problem because it is caused by fringe field

Use high Δn LC to reduce cell thickness



Simulated phase profile of liquid crystal device with different electrode configuration.

$\Delta n=0.35$, $d=2.5 \mu\text{m}$.

Pixel spacing= (a) 19.5 μm

(d) 4.5 μm

(b) 10.5 μm

(e) 2.5 μm

(c) 7.5 μm

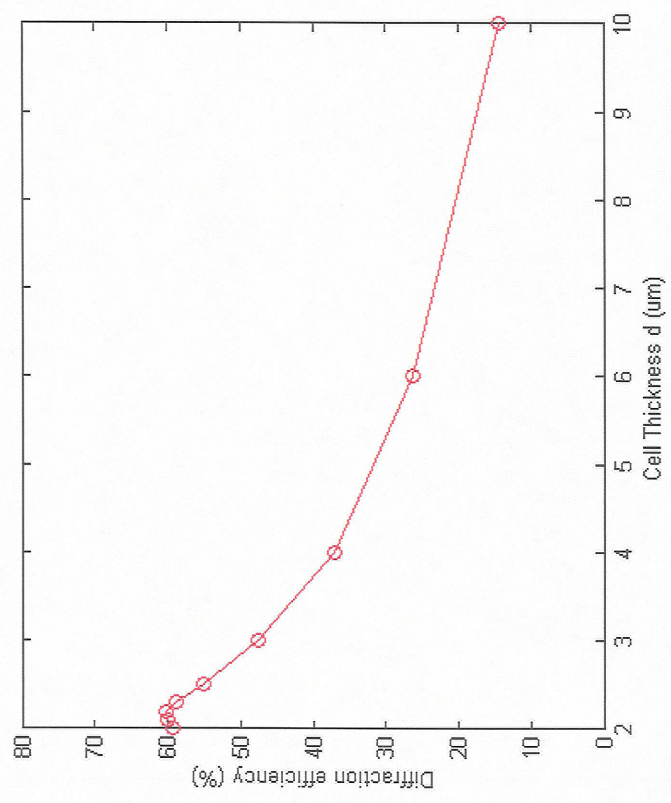
(f) 1.5 μm

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DE as function of Cell thickness (1550 nm)

Surprise: Highest DE occur at $\Delta n \cdot d / \lambda$ slightly smaller than 1

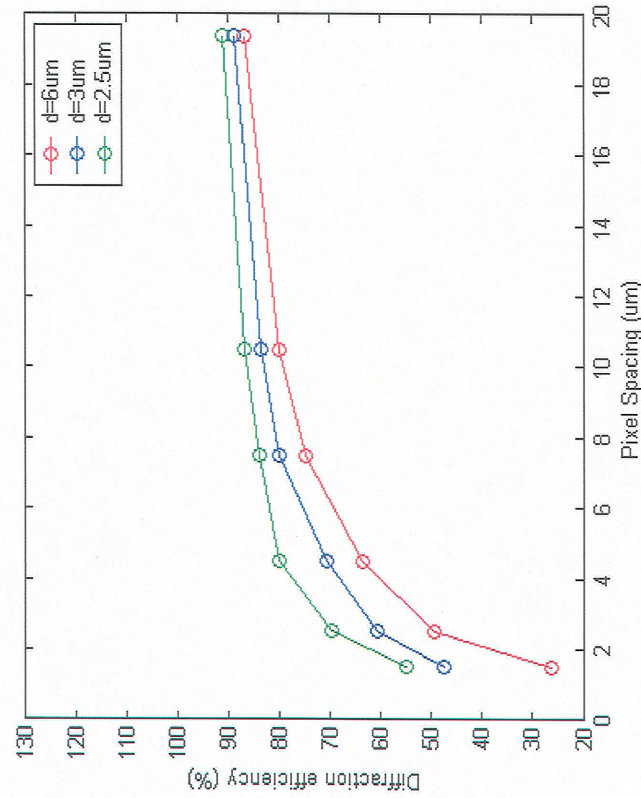
This is true only for very high spatial resolution LC OPA where fringe field is the dominate factor



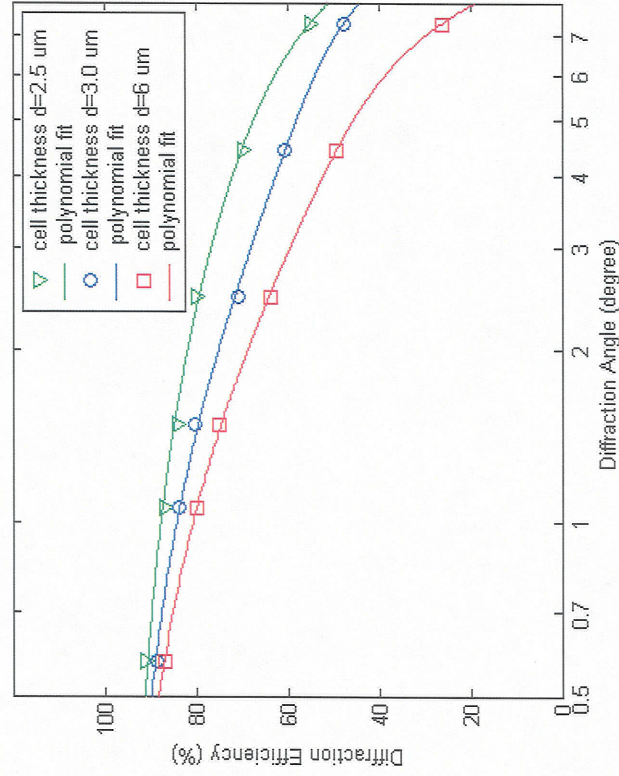
Diffraction efficiency Vs. cell thickness

	Δn	$d (\mu m)$	$\Delta n \cdot d / \lambda$	DE
1	0.350	1.9	0.86	59.2%
2	0.350	2.1	0.95	60.0%
3	0.350	2.3	1.04	58.9%
4	0.350	2.5	1.13	55.0%
5	0.350	3.0	1.16	48.9%
6	0.350	3.0	1.35	47.6%
7	0.300	4.0	1.80	37.2%

DE as function of steering angle(1550 nm)



(a)

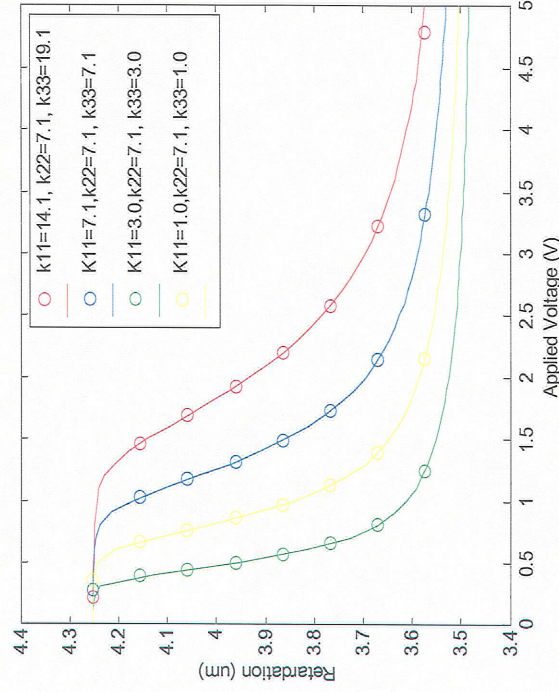


(b)

(a) Diffraction efficiency as function of pixel spacing.
 (b) the DE versus corresponding steering angle

Contribution of elastic constant

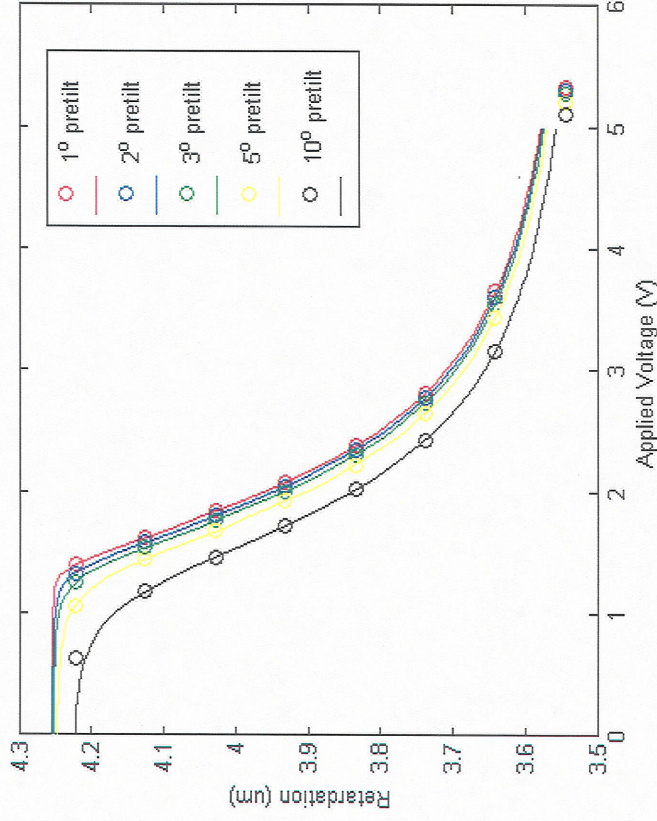
- Influence on DE is complicated and may not be very strong considering splay and bend elastic constant of LC as small as 10^{-12} N hasn't been found yet
- reduce the elastic constant leads to smaller driving voltage



- Using rubbing direction perpendicular to electrode (to lower effective elastic constant) may be a bad ideal
- Not much gain in DE but may cause depolarization

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Influence of pretilt

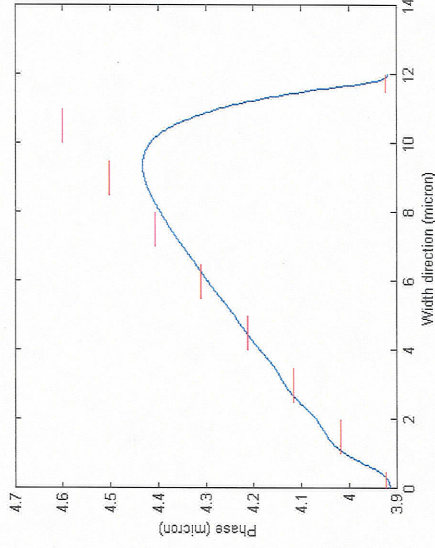
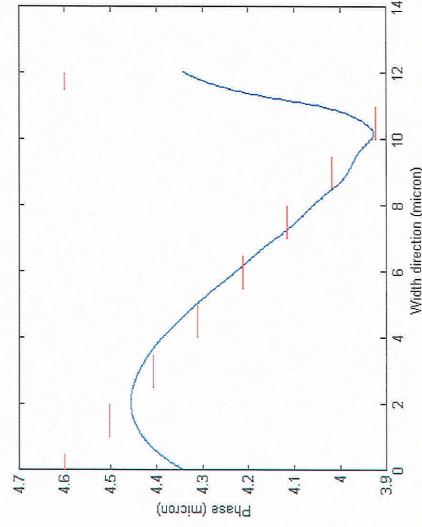


- Pretilt contributes little to DE when within (1~5°)
- Larger pretilt reduce the threshold voltage of LC at the same time reduce the total phase modulation depth

Pretilt	1°	3°	5°	10°
DE	53.4%	55.2%	55.1%	58.2%

+Trapped tilt wall configuration still needs more analyze

Non-symmetric induced by pretilt angle



Two effect:

- Non-symmetrical phase profile
- Non-symmetrical energy flow caused by non-symmetrical optical axis⁺

	$\Delta n=0.4$	$\Delta n=0.35$	$\Delta n=0.35$	$\Delta n=0.35$
	$d=2.0 \mu m$	$d=2.1 \mu m$	$d=2.3 \mu m$	$d=2.5 \mu m$
Steer to -1 diffraction order (corresponding to down tilt case)	59.2%	60.1%	58.9%	55.0%
Steer to +1 diffraction order (corresponding to up tilt case)	66.1%	60.0%	61.0%	57.5%

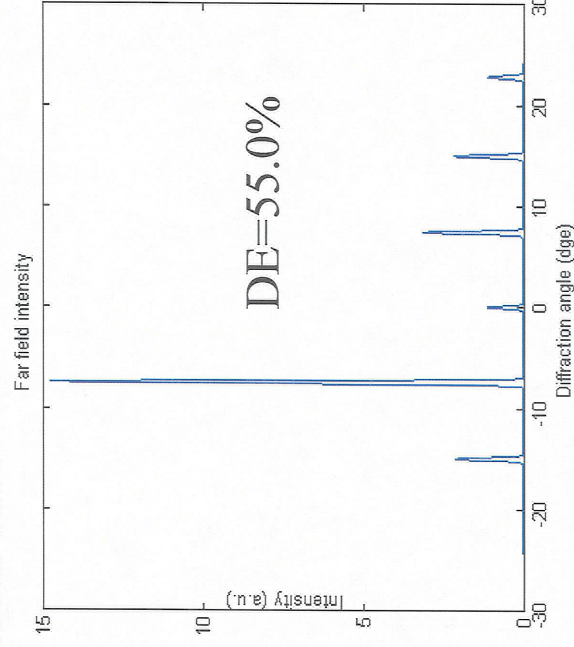
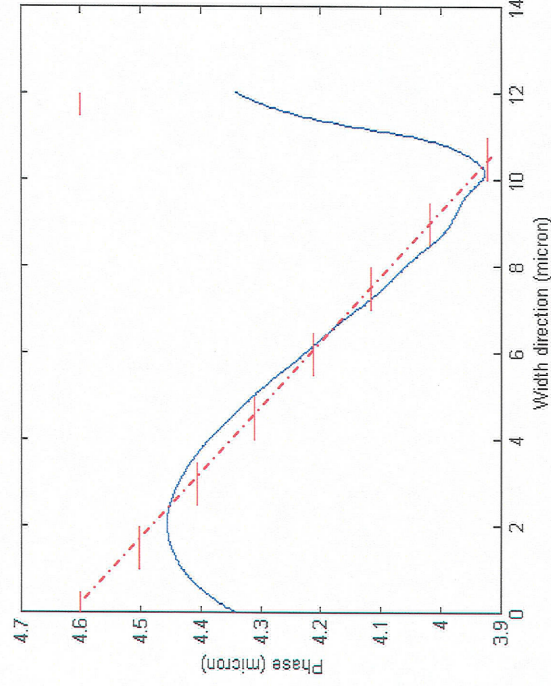
+ C. M. Titus, Optics Letters, Volume 26, Issue 15, 1188-1190, 2001

Optimization of voltage profile

At high spatial resolution, driving voltage (or EO response curve) measured by assuming a single pixel across aperture is not accurate any more:

Leads to:

1. Lower phase modulation at resets
2. Slope of phase profile deviate from ideal case

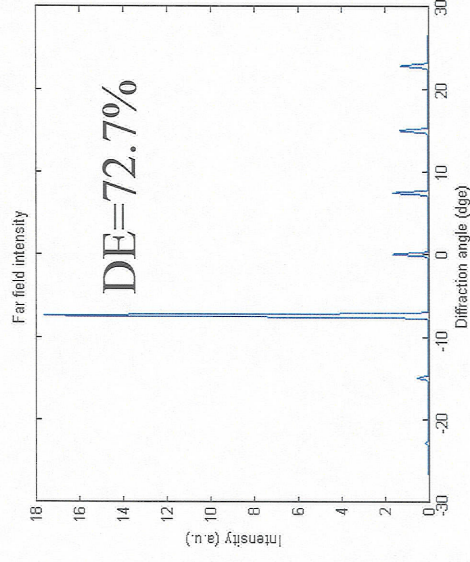
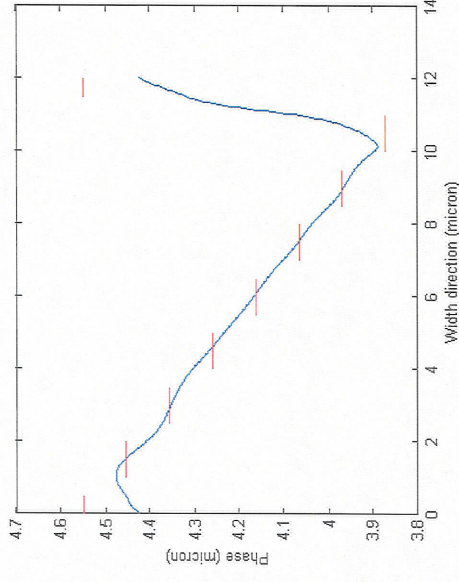
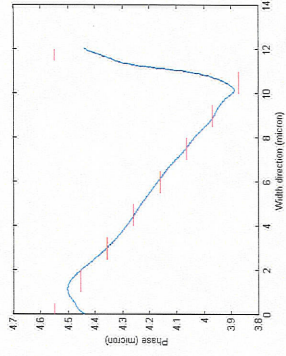
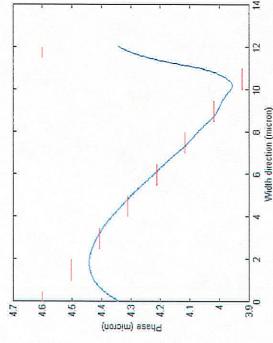


Phase profile (left) and far field without Voltage optimization

Optimization of voltage applied to each pixel will increase DE dramatically

Phase profile after voltage optimization

Intermediate iteration steps

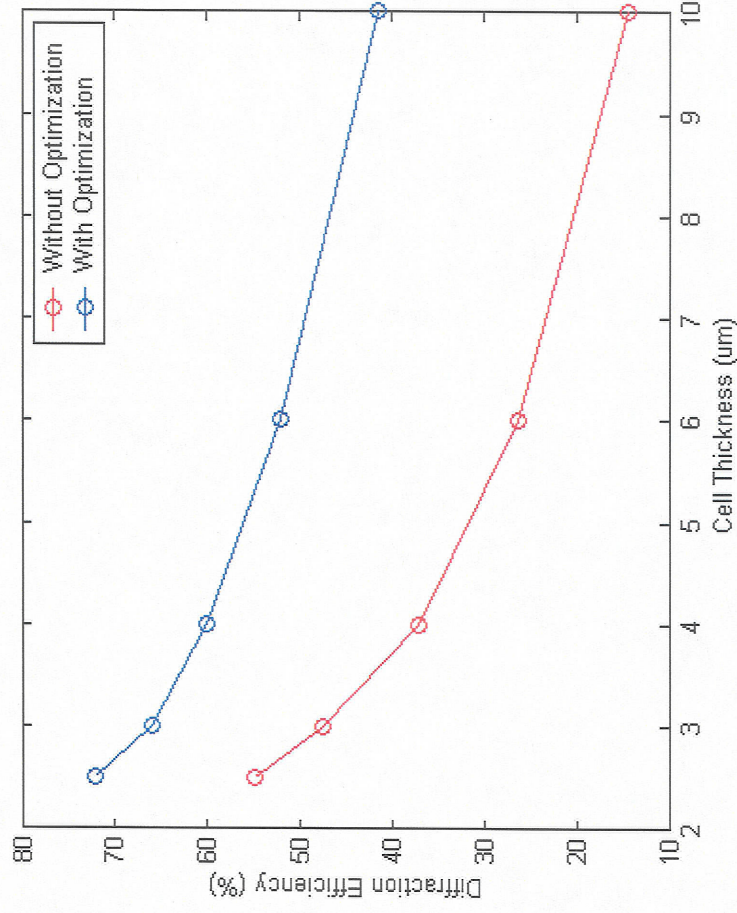


$\pm 7.4^\circ$ steering with DE=72.7%, for 1550 nm

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DE after voltage optimization



Diffraction efficiency as function of cell thickness, before and after voltage optimization

Thin cells have less benefit to optimize voltage profile

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Conclusion

- The most important influence factor to diffraction efficiency with LC OPA is cell thickness and voltage profile.
- It is possible to achieve higher than 72.7% of DE with $\pm 7.4^\circ$ steering for near IR wavelength 1550 nm

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